TROPICAL STORM STEERING USING GEOSTROPHIC WINDS DERIVED FROM SMOOTHED 700-MB AND 500-MB HEIGHT FIELDS

JAMES STEWART HARDIE

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by

James Stewart Hardie
Lieutenant, United States Navy
B.S., Oregon State College, 1959

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ABSTRACT

A numerical method for predicting the movement of tropical storms has been developed utilizing smoothed 700-mb (Atlantic area) and 500-mb (Pacific area) height fields as produced by the Fleet Numerical Weather Facility, Monterey, California. Geostrophic steering components are computed from the contour analyses at or near forecast time for predicting storm positions up to 72 hours. Recent-history vector forecast errors are employed as corrections to improve the basic steering forecast for periods up to 36 hours. Testing of storms from 15 August to 1 November 1965 in both Atlantic and Pacific regions indicates the method is comparable in accuracy to official forecasts as published by Fleet Weather Central/Joint Typhoon Warning Center, Guam, and Fleet Weather Facility, Jacksonville, Florida, as well as to Atlantic-area forecasts made with the NHC-64 statistical approach for periods up to 48 hours.

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SR ( )	FNWF residual height field at ( ) mb
Z	height of mandatory pressure level
Z_{SR}	residual height of mandatory pressure level
Z_{SD}	disturbance height of mandatory pressure level
$\vec{V}_g$	vector geostrophic wind as computed from Z_{SR} field
V_{gx}	scalar geostrophic wind in x direction
V_{gy}	scalar geostrophic wind in y direction
g	gravity
f	coriolis parameter, $2\omega \sin\theta$
ω	angular speed of the earth
θ	latitude
x,y	scalar coordinates coincident with I, J axes of FNWF grid
$\hat{i},\hat{j}$	unit vectors along cartesian coordinate axes x,y
M	map scale factor
D	mesh length, 381 km at latitude 60 N
I,J	grid points in the 63 x 63 hemispheric grid
m	meridional
z	zonal
$\vec{E}_n$	vector error for forecast interval n
$\hat{m},\hat{z}$	unit vectors along latitude, longitude
T_t	the latitude or longitude position of storm from best track, for the t^{th} hour
F_t	forecast latitude or longitude position of storm for the t^{th} hour
F_t'	forecast latitude or longitude position of storm, with recent-history error applied, for the t^{th} hour

F_t'' forecast latitude or longitude position of storm, with multiples of the 12-hour recent-history error applied, for the t^{th} hour

F_t''' forecast latitude or longitude of storm, with weighted recent-history errors applied, for the t^{th} hour

W_n weighting factor applied to each E_n

W factor adjusting weights, W_n, for forecast interval

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1. Introduction

Many methods for forecasting tropical storm[1] movement have been developed in the past ten years. Presently the most successful are the statistical approaches (1). Some examples are AROWA, Travelers-1966, Wang, Fairless, and NHC-64 (2)(3). Of increasing accuracy are the numerical models used at Fleet Numerical Weather Facility (FNWF), Monterey, California, and at the Environmental Sciences Services Administration (ESSA), Suitland, Maryland. These methods employ parameters such as 700-mb and 500-mb steering, persistance, climatology, thickness and sea level pressure parameters. Most desirable is a dynamic approach to forecasting tropical storm movement but at present dynamic steering models cannot fully compete with the statistical and subjective approaches. This is, in part, due to the fact that data networks in tropical areas are not dense enough.

[1]The term tropical storm as used throughout the text includes depression, storm, and hurricane/typhoon stages.

2. Background

In October 1966 Lt. J. E. Kerr, Naval Postgraduate School (PGS), Monterey, California, investigated the feasibility of a geostrophic steering model using FNWF's so-called SR fields (see Section 4) at various mandatory levels (4). His method was, in fact, similar to the geostrophic steering program used operationally by FNWF (5), but with all empirical and climatological factors eliminated.

Kerr's investigation led to results for 12- and 24-hour forecasts which appear competitive with the official forecasts as published by Fleet Weather Central, Guam, Mariana Islands (2), and Fleet Weather Facility, Jacksonville, Florida (3).

Specifically, Kerr's work indicates that for 12-hour forecasts the 1000-mb SR steering is best for the Atlantic hurricanes and the 500-mb SR steering is best for the Pacific typhoons. His 24-hour experiments show the 500-mb steering to excel when modified by a statistically derived correction based on direction of movement and position of the storm. Kerr's results are presented in tables 1 and 2. All averages were computed relative to each storm with no weighting for number of forecasts made. However, if the average of the individual forecasts is calculated and compared to the official forecast errors, computed similarly, then the accuracy of Kerr's approach is highlighted still further. Table 3 displays Kerr's figures alongside the recomputed averages. As an example, for 91 12-hour forecasts in the Atlantic, using the SR 1000-mb field, Kerr's average vector error becomes 99 nm vice 101 nm while the official forecast error for 137 forecasts improves to 86 vice 94 nm. Other comparisons are self-evident.

3. Aims

In view of Kerr's results and recommendations (4) and the demands of operational forecasting the aims of this study may be stated as follows:

a. Search for the optimum geostrophic steering level. Include the 700-mb level in such a search in view of the disparity of results regarding the best level in the Pacific and Atlantic areas.

b. Extend the forecast period, using the optimum forecast level, to 36, 48 and 72 hours and compare the results to the official forecasts as well as to a single outstanding statistical forecast approach (as NHC-64 in the Atlantic area).

c. Find a statistical modification to the results in a and b above in order to closely approach a plateau of forecast skill commensurate with data density, accuracy of observations, and methods of numerically processing input data and computed parameters at FNWF.

4. Numerical Procedures

The SR fields may be viewed as long-wave or macroscale height patterns which result from a mathematical decomposition, as developed by Holl (6). An SR height (Z_{SR}) is related to the observed height, Z, as follows:

$$Z = Z_{SR} + Z_{SD} \tag{1}$$

where Z_{SD} refers to the disturbance height field which is closely related to the short or minor wave components of the height field. For the purpose of tropical storm forecasting the storm may be considered an SD feature, thus the SR field is tantamount to the residual height field which results upon removing the storm's circulation.

The geostrophic steering equation as applied to the SR field may be stated as

$$\vec{V}_g = -g/f \left(\frac{\partial Z_{SR}}{\partial y} \hat{i} - \frac{\partial Z_{SR}}{\partial x} \hat{j} \right) \tag{2}$$

$$\vec{V}_g = V_{gx} \hat{i} + V_{gy} \hat{j} \quad . \tag{3}$$

In finite difference form, equation (2) becomes

$$\vec{V}_g = \frac{-gM}{2fD} \left[\left(Z_{SR\,I}^{J+1} - Z_{SR\,I}^{J-1} \right) \hat{i} - \left(Z_{SR\,I+1}^{J} - Z_{SR\,I-1}^{J} \right) \hat{j} \right] . \tag{4}$$

An example of using this equation on a linear grid is shown in figure (1). Here the grid points, I and J, are equivalent to that in the FNWF operational grid but I and J points are not necessarily located at whole-numbered FNWF grid points. The storm location to the nearest .1° latitude and longitude determines position I, J.

To avoid division by very small numbers in equatorial latitudes, the sine function, as used in the coriolis parameter, f, is modified to

$$2\left[\left(\frac{\sin\theta}{4} + \frac{1}{4} \right)^2 + \frac{\sin\theta}{4} \right] .$$

The graph of this function is shown in figure (2).

The steering program was run on the PGS CDC 1604 computer. The input data were best track latitude and longitude of the tropical storm at 0600 and 1800 GMT (I, J on figure 1) except for Atlantic storm Carol for which 0000 and 1200 GMT positions were used. The SR field at 1200 or 0000 GMT (i.e. six hours after time of storm positions, except for Carol) was selected and the four points I, J+1; I+1, J; I, J-1; I-1, J were located at standard FNWF grid distances from I, J. The meridional and zonal geostrophic wind components were then computed by equation (4) for each of the four points. The storm (I, J) was steered for one hour with the mean of these components. This process was repeated for the required number of one-hour time steps, for forecasts at 12-hour intervals, up to 72 hours. Only the <u>single SR analysis</u> selected for the input time was utilized.

5. Testing and Results

The procedure outlined in section four was used to forecast the movement of the 1965 tropical storms for the Atlantic and Pacific areas for intervals up to 72 hours. All storms from mid-August to 1 November 1965 were processed. However, because of technical difficulties, results for all forecast intervals and techniques developed in this study are not available for all tropical storms in this period. This period includes all storms in the Atlantic area for the year 1965.

Since Kerr computed forecasts for 12 and 24 hours using SR 500, this study first concerned itself with the extension of such forecasts to 36, 48 and 72 hours (see table 4). The figures are the mean vector errors, in nautical miles, with the official mean vector errors listed for comparison. Kerr's 12- and 24-hour forecasts are included. The figures in paranthesis are the number of forecasts used to compute the average.

The Atlantic tropical storm summary has individual storm official errors for 12- and 24-hour forecasts only, while overall averages are given for 12-, 24-, 48- and 72-hour forecasts (3). In the case of typhoons, individual and overall average vector errors were published for 24, 48 and 72 hours (2).

At this point of the investigation the accuracy of the SR forecasts approach but do not show skill relative to the official forecasts, with one exception, the 72-hour Atlantic forecasts. However, the trend of accuracy of SR 500 forecast errors relative to official forecasts improves with increasing forecast interval, especially for the Atlantic storms.

Since Kerr indicated relative success in the Atlantic using SR 1000-mb fields for 12-hour forecasts, it was decided to experiment with

SR 700, comparing results to 1000-mb in the Atlantic for 12-hour forecasts and to SR 500 in the Pacific for all time intervals. With reference to the 12- and 24-hour forecasts using SR 700 in table 5, it became apparent that the 700-mb SR fields did not fare as well as the 500-mb SR fields in the Pacific, with the ratio of the average 12- (24-) hour SR 500 to SR 700 80/100 (172/183) nautical miles. Bess at 12 hours and Mary at 24 hours provided exceptions to the average result. In the Atlantic the SR 700 excelled SR 500 with the ratio of the average 12-(24-) hour SR 500 to SR 700 108/91 (192/177) with Carol a slight exception to the average result for the 24-hour forecast.

Since Kerr regarded the SR 500 to be better than the SR 1000 for 24-hour forecasts in the Atlantic and in view of the results shown in table 5, the 700-mb SR steering was extended to 72 hours in the Atlantic only. Results are shown in table 6.

Upon comparing table 6 to table 4, it is seen that although SR 700 is, overall, an improvement over SR 500, the relative accuracy of the former to the latter decreases consistently from the 12-to the 72-hour forecast. In fact by 72 hours the SR 500 is better (489 nm) than SR 700 (495 nm) but the sample is not homogeneous so the trend may not be valid.

In attempting to develop an objective method for statistically improving the SR forecasts, the track derived from prognostic positions was compared with the best track. It was apparent that the tracks were similar in shape but differed in coincidence of forecast and verifying positions (figure 3). This observation suggested application of a correction to the basic SR forecast using the recent-history vector forecast error. The technique is described symbolically in the following equations.

The vector error ($\vec{E}$) for a 12-hour forecast as dependent on best track (T) and forecast (F) positions may be represented as follows:

$$\vec{E}_{12} = \vec{E}_{m12} + \vec{E}_{z12} \qquad (5)$$

where m and z refer to the meridional and zonal components of the error. In greater detail,

$$\vec{E}_{m12} = \left[(T_0 - T_{-12}) - (F_0 - T_{-12})\right]_{m12} \hat{m} \qquad (6a)$$

and

$$\vec{E}_{z12} = \left[(T_0 - T_{-12}) - (F_0 - T_{-12})\right]_{z12} \hat{z}\,. \qquad (6b)$$

Thus,

$$|\vec{E}_{m12}| = (T_0 - F_0)_{m12} \qquad (7a)$$

and

$$|\vec{E}_{z12}| = (T_0 - F_0)_{z12} \qquad (7b)$$

Modified 12-hour forecast storm positions, F'_{12}, starting from initial conditions at time "0", are represented by equations (8a) and (8b).

$$F'_{m12} = F_{m12} + (T_0 - F_0)_{m12} \qquad (8a)$$

$$F'_{z12} = F_{z12} + (T_0 - F_0)_{z12} \qquad (8b)$$

Forecasts for 24, 36, 48 and 72 hours employ the 24-, 36-, 48- and 72-hour recent-history vector error corrections, respectively. See figure (4) for a vector diagram of a 12-hour modified forecast.

Application of such a correction showed considerable improvement in the 12-, 24- and 36-hour forecasts. As noted in tables 7, 8 and 9, the average errors dramatically decrease from 73 to 46 nm, 172 to 105 nm, and 248 to 185 nm for 12-, 24-, and 36-hour forecasts in the Pacific, and from 91 to 49 nm, 177 to 126 nm, and 262 to 251 nm for 12-, 24- and 36-hour forecasts in the Atlantic. Every storm except Mary at 12-hours showed improvement in the first two forecast intervals. Anna, Betsy, Debbie, and Virginia showed deterioration with the recent-history correction at 36 hours. At 48 hours the overall average vector error for the modified forecast was smaller (table 10) in the Pacific but higher in the Atlantic with most storms behaving like the average. At 72 hours (table 11) the overall average error with the history-error correction did not improve the Atlantic or Pacific forecasts.

In an effort to improve the longer range forecasts, especially where the largest forecast errors occurred during the recurvature period the most recent 12-hour errors were computed as in the above equations and applied to the 48-hour forecasts in appropriate 12-hour multiples of the forecast intervals. In the case of a 48-hour forecast the vector error is applied as in equations (9a, 9b) below.

$$F''_{m_{48}} = F_{m_{48}} + 4(T_0 - F_0)_{m12} \qquad (9a)$$

$$F''_{z_{48}} = F_{z_{48}} + 4(T_0 - F_0)_{z12} \qquad (9b)$$

This approach has shown some improvement in reducing the overall vector errors in forecast positions, but frequently the tracks connecting prognostic positions become erratic. Figure 5 shows an example for Carmen.

Table 10 shows the improvement in the history-error modifications by emphasizing the corrections due to the more recent error (F'').

In the Atlantic the F'' error (345 nm) closely matches the F error (346 nm) while in the Pacific an F'' error of 180 nm is a marked improvement over F and F' with 269 and 230 nm,respectively.

A logical extension of the above modification technique involves a weighting of short-term and long-term vector forecast errors in order to incorporate the most recent trend into the forecast along with the longer-term corrections.

In the case of a 48-hour forecast, application to the meridional component may be symbolically stated as follows:

$$F'''_{m48} = F_{m48} + \frac{W_{12}}{W}(T_0 - F_0)_{m12} + \frac{W_{24}}{W}(T_0 - F_0)_{m24} + \frac{W_{48}}{W}(T_0 - F_0)_{m48} \quad (10)$$

where W_n and W are weighting factors dependent on the forecast interval, 48 hours, and the intervals 12, 24 and 48 hours, from which the errors are computed. As an example, weighting the 12-hour forecast error by 4, $(=W_1)$, the 24-hour forecast error by 3, $(=W_2)$, and the 48-hour forecast error by 1 $(=W_4)$, while adjusting the weights for the 48-hour forecast interval by setting W equal to 3.5,

$$F'''_{m48} = F_{m48} + 1.14\left|\vec{E}_{m12}\right| + 0.86\left|\vec{E}_{m24}\right| + 0.29\left|\vec{E}_{m48}\right| \quad (11)$$

Limited results using this method for a 48-hour forecast, F'''_{48}, give a mean vector error of 228 nm for 10 forecasts of typhoon Carmen. This figure does not represent an improvement over F''_{48} (see table 10).

6. Comparison to NHC-64

In comparing the average vector errors of the optimum[2] forecast method of this investigation to the NHC-64 method, the subject method did better than NHC-64 in the 12-, 24- and 36-hour forecasts but worse than NHC-64 for 48-hour forecasts. Table 12 shows the results of this comparison. Forecasts from hurricane Carol by the subject method and NHC-64 were all at 0000 or 1200 GMT. NHC-64 forecasts for other storms were also made at 0000 or 1200 GMT while those from the subject method were at 0600 or 1800 GMT. For comparison to NHC-64 in the latter case the average of the 0600 and 1800 GMT forecasts on either side of the NHC-64 forecast was used. Although, as a consequence, the samples are not completely homogeneous, the results are similar if Carol alone or all storms are considered.

[2] Optimum forecast method in the Atlantic for this comparison was 700-mb SR steering with the F' recent-history correction for 12-, 24- and 36-hour forecasts and the unmodified 700-mb SR steering for the 48-hour forecasts.

7. Concluding Remarks

The numerical method of tropical storm steering as described here gives results which are comparable to or excel official forecasts for 12-, 24-, 36-, 48- and 72-hour forecasts. Moreover, with reference to the most accurate single statistical technique in the Atlantic area, NHC-64, the subject method shows excellence for the first 36 hours of the forecast interval. It should be noted that the method just outlined is strictly <u>objective</u> employing only <u>analyzed SR fields</u> with the <u>correction due to the recent-history error</u> being a substitute for the prognostic SR field by capturing the most recent trends of storm movement due to changes in the SR pattern. Also, use of the history modification corrects for use of an improper steering level as there is little doubt that a single such level is not appropriate for all storms.

Two pertinent facts concerning comparison of vector errors should be mentioned. One, the forecasts are biased in favor of this investigation because the initial input for the numerical computations employed the best track position while official forecasts were made from operational positions. The average distance of reconnaissance aircraft fixes from best track positions was 13 miles for all storms in the 1965 season in the Pacific (2) and considerably less in the Atlantic. Two, the difference between operational and best track positions may be considered of minor significance compared to the fact that the operational "12, 24, etc." forecasting period is generally longer than the research "12, 24, etc." forecast period. For example, Fleet Weather Central, Guam, files warnings every six hours (00, 06, 12, 18 GMT); the message contains a warning-time position which really represents a 3- to 12-hour extrapolation of the storm position using the last radar or reconnaissance fix, or most recent surface or upper-air reports. Thus a 24-hour forecast is, in effect, a 27- to 36-hour forecast.

8. Recommendations for Further Study

1. Apply the SR geostrophic steering technique to prognostic SR fields.

2. Check the validity of optimum results from the 1965 tests by further tests in the 1966 season.

3. Evaluate the subject method in the 1967 season under real-time operational conditions. Compare results to the present method employed by FNWF.

4. Stratify storm data by region, season, storm intensity, etc., and search for regression relations to improve upon the basic geostrophic SR steering (with or without history modification).

5. Continue tests of history modification by varying the weights in equation (11).

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	SR 1000	SR 500	SR 200	SR 1000/200	SR 500/200	SR 1000/500	Mean	Official
Hurricane								
Anna	60[1]	82				98	80	119
Betsy	78[1]	83	168	142	172	96	123	67
Carol	93[1]	127	290	143	171	101	154	105
Debbie	58[1]	89	208	167	196	90	135	65
Elena	215	194[1]	306	217	254	196	230	114
Average	101[1]	115	286	167	198	116	144	94
Typhoon								
Lucy	53[1]	84				133	90	
Mary	44	28[1]				65	46	
Olive	72	61[1]	112	121	139	81	98	
Rose	140	34[1]	356	168	234	77	168	
Shirley	140	122[1]	146	132	134	129	134	
Trix	134	97	92[1]	81	111	100	103	
Virginia	146	104[1]	181	191	260	132	169	
Bess	123	84	137	130	132	75[1]	114	
Carmen	131	67[1]	95	89	93	86	94	
Della	130	85[1]	136	134	128	117	122	
Average	111	77[1]	144	131	154	100	114	

[1] Least Forecast Error

Table 1

Hurricanes	Official Forecasts	SR 500	Modified SR 500
Anna	217	149	205
Betsy	130	157	146
Carol	192	181	151
Debbie	135	149	121
Elena	260	353	265
Average	187	198	177

Typhoons			
Lucy	169	216	236
Mary	107	111	111
Olive	138	129	141
Rose	55	139	139
Shirley	231	230	182
Trix	138	187	135
Virginia	289	200	182
Bess	106	120	105
Carmen	148	156	124
Della	152	196	189
Average	153	168	154

Table 2

Hurricanes	Average vector error by storm [from (4)]		Average vector error by individual forecasts	
	Kerr	Official	Kerr	Official
12 Hour SR 1000	101[5][1]	94[5]	99(91)[2]	86(137)
24 Hour SR 500 Mod.	177[5]	187[5]	166(84)	171(134)

Typhoons				
12 Hour SR 500	77[10]		80(109)	
24 Hour SR 500 Mod.	154[10]	153[10]	154(100)	148(199)

[1]Numbers in [ ] represent number of storms.

[2]Numbers in ( ) represent number of individual forecasts.

Table 3

	12 HOUR		24 HOUR		36 HOUR	48 HOUR		72 HOUR	
Hurricane:	SR	OFFICIAL	SR	OFFICIAL	SR	SR	OFFICIAL	SR	OFFICIAL
Anna	82(6)	119(6)	149(6)	217(4)	234(4)	322(3)			
Betsy	83(29)	67(57)	157(28)	130(56)	231(27)	308(26)		463(24)	
Carol	127(31)	105(38)	181(30)	192(40)	266(29)	352(28)		514(26)	
Debbie	89(10)	65(16)	149(9)	135(14)	220(8)	287(7)			
Elena	194(13)	114(20)	353(12)	260(20)	493(11)	510(10)			
Average[1]	114(89)	86(137)	192(85)	171(134)	279(79)	350(74)	346(112)	489(50)	
Average[2]									543(98)
Typhoon:									
Lucy	84(12)		216(11)	169(29)		353(10)	329(25)		481(19)
Mary	28(6)		111(6)	107(14)	187(5)	293(4)	154(10)		170(5)
Olive	61(6)		129(5)	138(17)			284(13)		449(9)
Rose	34(9)		139(8)	55(15)	199(7)	254(6)	127(11)		245(3)
Shirley	122(13)		230(12)	231(16)	335(11)	425(10)	589(12)		871(3)
Trix	97(14)		187(13)	138(27)	275(12)	348(11)	302(23)	401(9)	426(18)
Virginia	104(6)		200(5)	289(11)	318(4)	418(3)	615(7)		1055(3)
Bess	84(14)		120(13)	106(26)	173(12)	229(11)	256(22)	360(9)	401(16)
Carmen	67(17)		156(16)	148(21)	223(15)	307(14)	238(15)	441(12)	289(11)
Della	85(12)		196(11)	152(23)	286(9)	366(9)	277(17)	550(6)	484(11)
Average[1]	80(109)		172(100)	148(199)	248(75)	334(78)	306(142)	444(36)	403(56)
Average[2]				151(405)			314(303)		418(208)

[1]Average for only those storms forecasted by both methods.

[2]Official forecast averages of storms for the calendar year 1965 (2)(3).

Table 4

Hurricanes	12 Hour SR 700	12 Hour SR 500	24 Hour SR 700	24 Hour SR 500
Anna	70(8)	82(6)	127(7)	149(6)
Betsy	72(31)	83(29)	141(31)	157(28)
Carol		127(31)	183(29)	181(30)
Debbie	54(9)	89(10)	112(9)	149(9)
Elena	170(14)	194(13)	328(13)	353(12)
Average[1]	91(62)	108(58)	177(89)	192(85)
Average[2]		114(89)		
Typhoons				
Lucy	98(16)	84(12)		216(11)
Mary	55(8)	28(6)	106(7)	111(6)
Olive	77(8)	61(6)	156(8)	129(5)
Rose	117(9)	34(9)	204(8)	139(8)
Shirley	131(13)	122(13)	232(12)	230(12)
Trix	108(15)	97(14)	188(14)	187(13)
Virginia	108(7)	104(6)	202(6)	200(5)
Bess	81(12)	84(14)	151(10)	120(13)
Carmen	103(16)	67(17)	186(15)	156(16)
Della	100(13)	85(12)		196(11)
Average[1]	100(117)	80(109)	183(80)	158(78)
Average[2]				172(100)

[1] Average for only those storms forecasted by both SR 700 and SR 500.

[2] Average for all storms forecasted by method given in column heading.

Table 5

	12 Hour	24 Hour	36 Hour	48 Hour	72 Hour
Hurricanes					
Anna	70(8)	127(7)	189(6)	284(5)	524(3)
Betsy	72(31)	141(31)	205(30)	273(29)	399(26)
Carol		183(29)	276(28)	363(28)	
Debbie	54(9)	112(9)	173(8)	220(6)	261(5)
Elena	170(14)	328(13)	471(12)	595(11)	857(9)
Average	91(62)	177(89)	262(82)	346(79)	495(43)

Table 6

Hurricanes SR 700	F_{12}	F'_{12}
Anna	70(8)	47(7)
Betsy	72(31)	45(30)
Carol		45(29)
Debbie	54(9)	28(8)
Elena	170(14)	71(13)
Average[1]	91(62)	49(58)
Average[2]		48(87)

Typhoons SR 500		
Lucy	84(12)	59(8)
Mary	28(6)	44(5)
Olive	61(6)	
Rose	34(9)	34(8)
Shirley	122(13)	46(12)
Trix	97(14)	47(12)
Virginia	104(6)	45(4)
Bess	84(14)	49(13)
Carmen	67(17)	50(16)
Della	85(12)	52(10)
Average[1]	73(103)	46(88)
Average[2]	80(109)	

[1]Average for only those storms forecasted by both F_{12} and F'_{12}.

[2]Average for all storms forecasted by method given in column heading.

Table 7

Hurricanes SR 700	F_{24}	F_{24}'
Anna	127(7)	126(5)
Betsy	141(31)	113(29)
Carol	183(29)	113(26)
Debbie	112(9)	99(7)
Elena	328(13)	226(11)
Average	177(89)	126(78)

Typhoons SR 500		
Lucy	216(11)	107(7)
Mary	111(6)	95(3)
Olive	129(5)	112(2)
Rose	139(8)	58(6)
Shirley	230(12)	163(10)
Trix	187(13)	118(10)
Virginia	200(5)	94(2)
Bess	120(13)	85(11)
Carmen	156(16)	89(14)
Della	196(11)	115(7)
Average	172(100)	105(72)

Table 8

Hurricanes SR 700	F_{36}	F'_{36}
Anna	189(6)	269(3)
Betsy	205(30)	230(30)
Carol	276(28)	217(25)
Debbie	173(8)	202(5)
Elena	471(12)	436(9)
Average	262(84)	251(72)

Typhoons SR 500		
Lucy		130(5)
Mary	187(5)	152(2)
Olive		
Rose	199(7)	100(4)
Shirley	335(11)	308(8)
Trix	275(12)	236(8)
Virginia	318(4)	329(1)
Bess	173(12)	137(9)
Carmen	223(15)	145(12)
Della	287(9)	142(5)
Average[1]	248(75)	185(49)
Average[2]		180(54)

[1]Average for only those storms forecasted by both F_{36} and F'_{36}.

[2]Average for all storms forecasted by method given in column heading.

Table 9

Hurricanes SR 700	F_{48}	F'_{48}	F''_{48}
Anna	284(5)	432(1)	586(1)
Betsy	273(29)	353(25)	302(25)
Carol	363(28)	349(24)	325(24)
Debbie	220(6)	315(3)	291(3)
Elena	595(11)	695(7)	558(7)
Average	346(79)	397(60)	345(60)

Typhoons SR 500	F_{48}	F'_{48}	F''_{48}
Lucy	353(10)	267(6)	
Mary	293(4)		
Olive			
Rose	254(6)	128(2)	173(2)
Shirley	425(10)	419(6)	
Trix	348(11)	438(7)	
Virginia	418(3)		
Bess	229(11)	211(7)	183(7)
Carmen	307(14)	264(10)	186(10)
Della	366(9)	169(4)	
Average[1]	269(31)	230(19)	180(19)
Average[2]	327(71)	293(42)	
Average[3]	334(78)		

[1]Average for only those storms forecasted by F_{48}, F'_{48}, and F''_{48}.

[2]Average for only those storms forecasted by F_{48} and F'_{48}.

[3]Average for all storms forecasted by F_{48}.

Table 10

Hurricanes SR 700	F_{72}	F'_{72}
Anna	524(3)	
Betsy	399(26)	551(20)
Carol		
Debbie	261(5)	
Elena	857(9)	1363(3)
Average[1]	517(35)	619(23)
Average[2]	495(43)	

Typhoons SR 500		
Trix	401(9)	707(3)
Bess	360(9)	285(3)
Carmen	441(12)	528(6)
Della	550(6)	41(1)
Average	444(36)	471(13)

[1]Average for only those storms forecasted by both F_{72} amd F'_{72}.

[2]Average for all storms forecasted by method given in column heading.

Table 11

	12 Hour	24 Hour	36 Hour	48 Hour
SR 700 forecasts for Hurricane Carol only	39(15)	105 (14)	175(15)	330(15)
NHC-64 forecasts for Hurricane Carol only	117(15)	143(14)	215(15)	302(15)
SR 700 forecasts[1]	40(48)	121(42)	210(37)	297(42)
NHC-64 forecasts[1]	85(48)	130(42)	227(37)	267(42)

[1] Averages for only those forecasts for which data were available for both methods.

Table 12

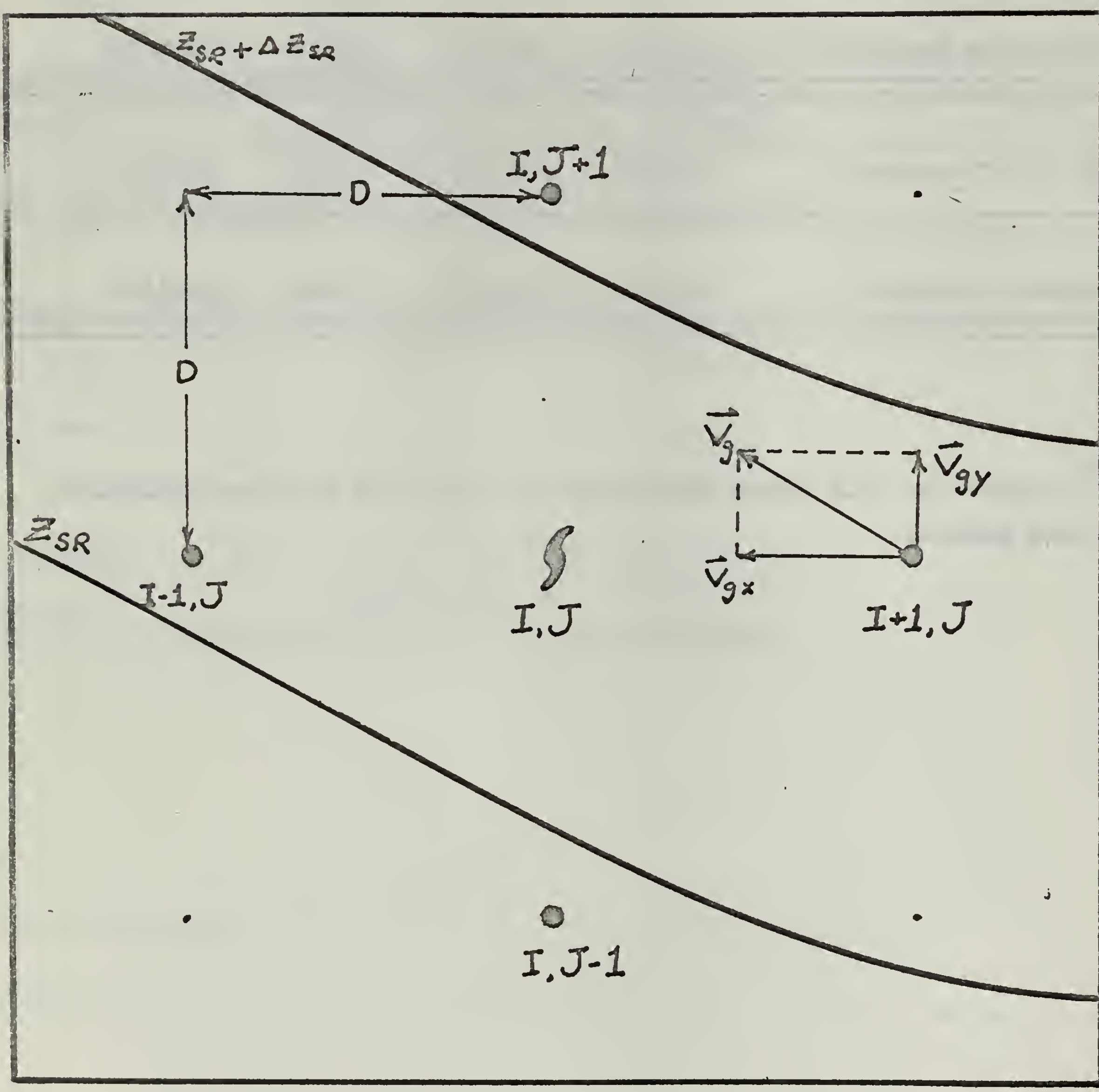


Figure 1

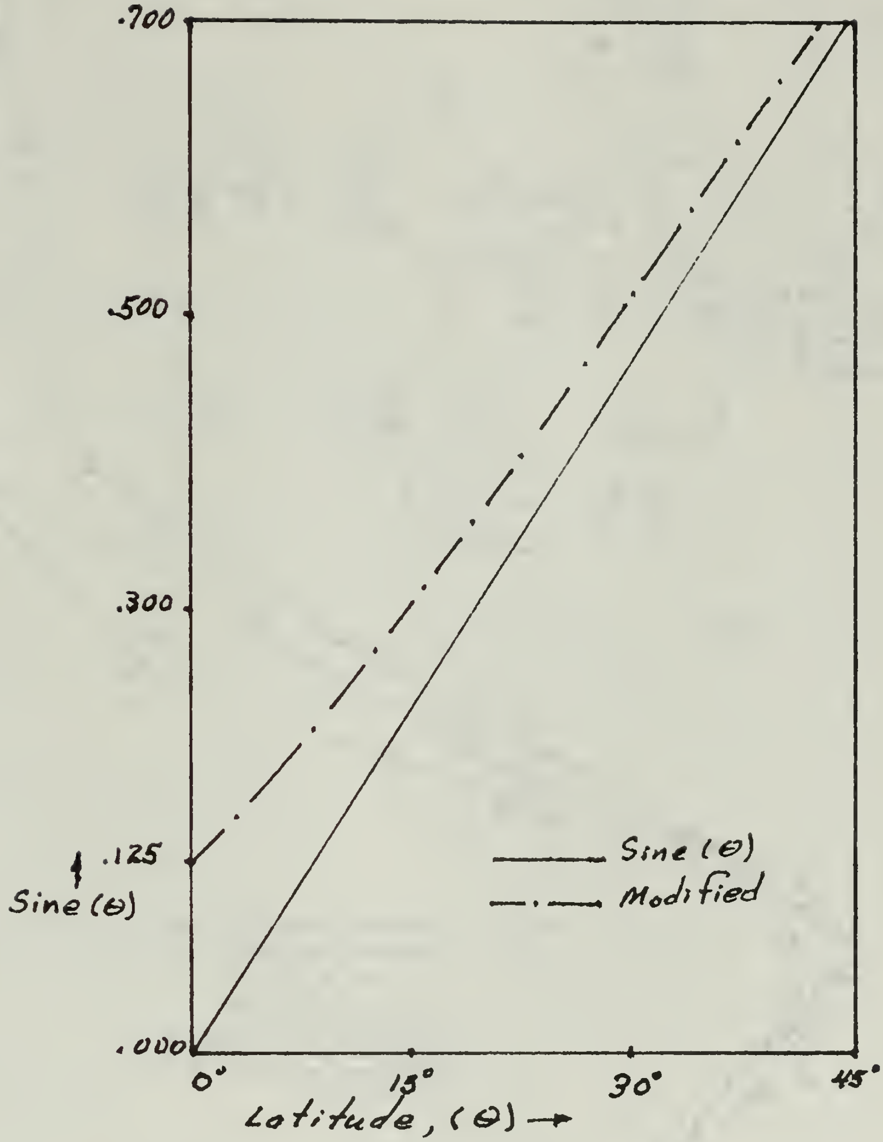
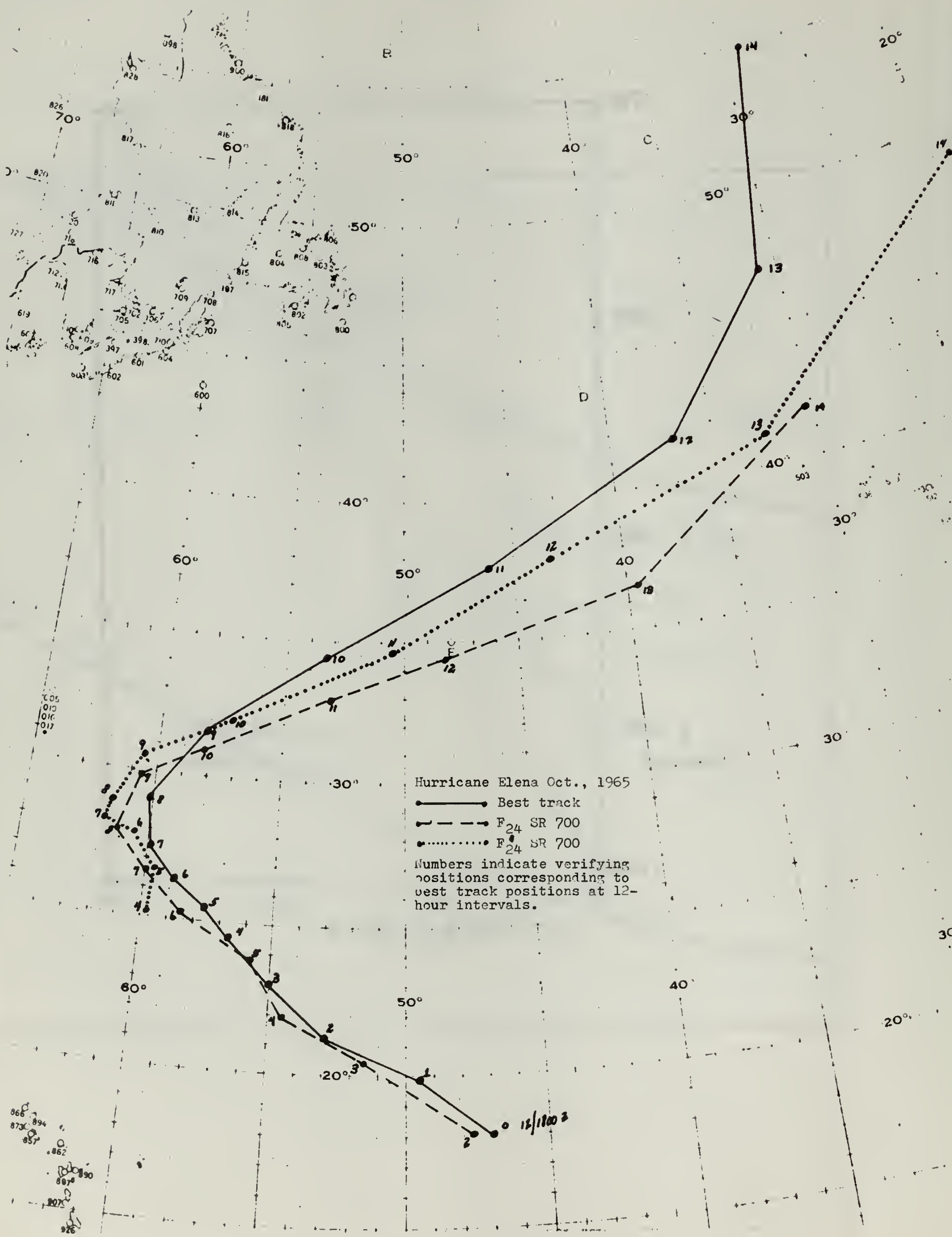


Figure [illegible]



Hurricane Elena Oct., 1965
Best track
F24 SR 700
F24 SR 700
Numbers indicate verifying positions corresponding to best track positions at 12-hour intervals.
12/1800Z

Figure 3

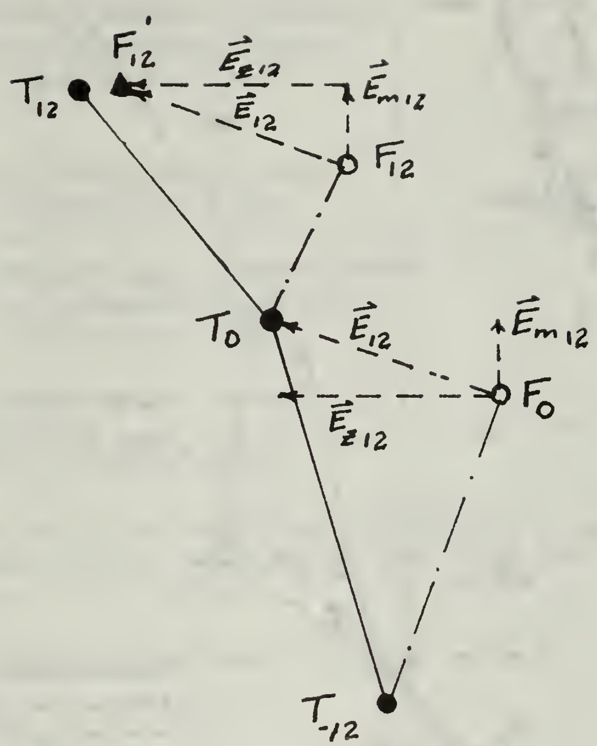

F_{12}'
$\vec{E}_{z12}$
T_{12}
$\vec{E}_{m12}$
$\vec{E}_{12}$
F_{12}
T_0
$\vec{E}_{12}$
$\vec{E}_{m12}$
F_0
$\vec{E}_{z12}$
T_{-12}

Figure 4

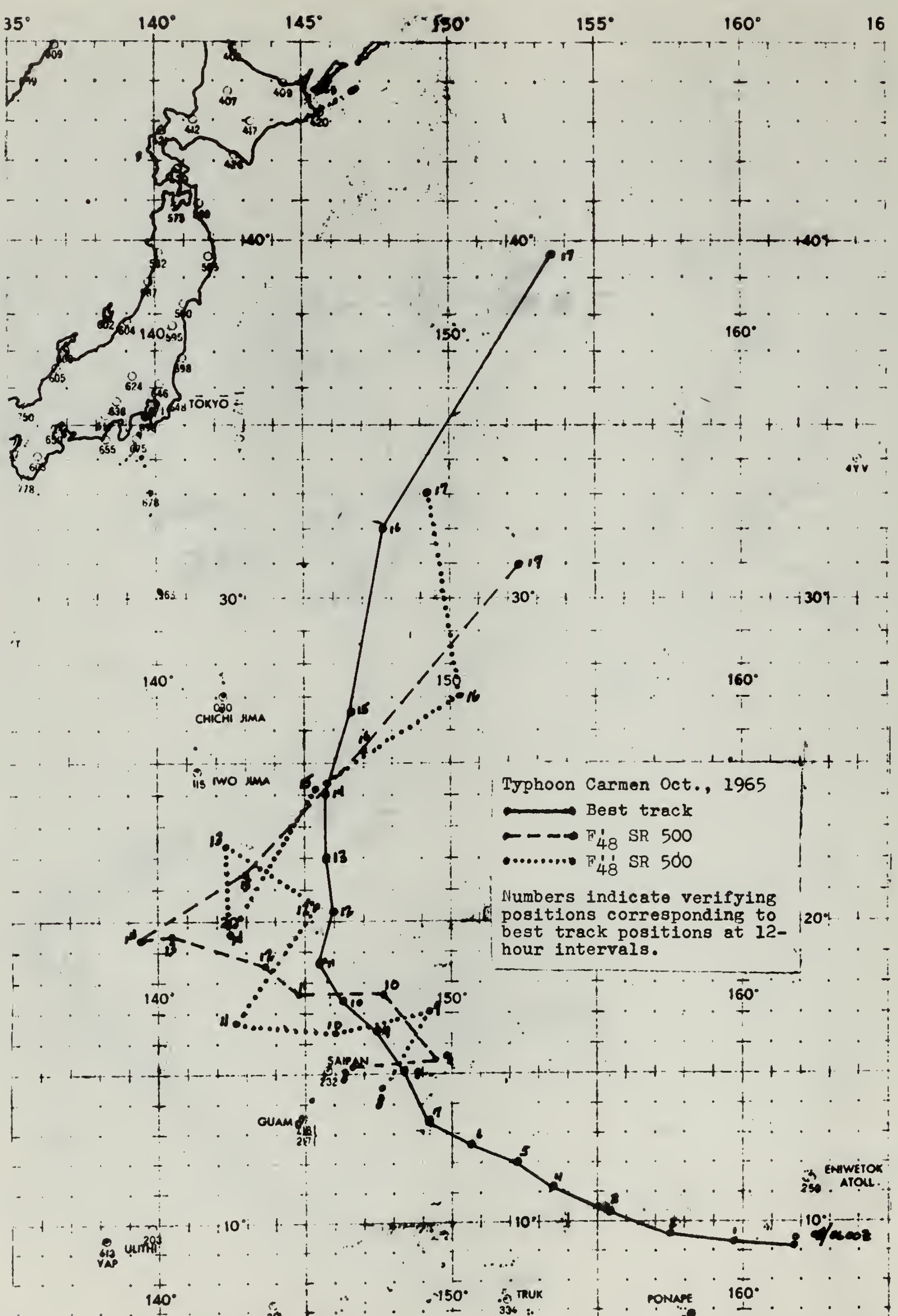

Typhoon Carmen Oct., 1965
Best track
F'_{48} SR 500
F''_{48} SR 500
Numbers indicate verifying positions corresponding to best track positions at 12-hour intervals.
TOKYO
CHICHI JIMA
IWO JIMA
SAIPAN
GUAM
ULITHI
YAP
WOLEAI ATOLL
TRUK
PONAPE
KUSAIE
ENIWETOK ATOLL

Figure 5

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13. ABSTRACT

A numerical method for predicting the movement of tropical storms has been developed utilizing smoothed 700-mb (Atlantic area) and 500-mb (Pacific area) height fields as produced by the Fleet Numerical Weather Facility, Monterey, California. Geostrophic steering components are computed from the contour analyses at or near forecast time for predicting storm positions up to 72 hours. Recent-history vector forecast errors are employed as corrections to improve the basic steering forecast for periods up to 36 hours. Testing of storms from 15 August to 1 November 1965 in both Atlantic and Pacific regions indicates the method is comparable in accuracy to official forecasts as published by Fleet Weather Central/Joint Typhoon Warning Center, Guam, and Fleet Weather Facility, Jacksonville, Florida, as well as to Atlantic-area forecasts made with the NHC-64 statistical approach for periods up to 48 hours.

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